On the Efficiency of Selenium as a Detector of Light.

By E. E. Fournier d'Albe, D.Sc. (Birm.).

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The following investigation concerns the limits up to which minute quantities of light and minute variations of its intensity may be discovered by means of selenium.

There are two actions of light on selenium which may be used—(1) a change in the conductivity, first described by W. Smith in 1873; and (2) the generation of an E.M.F. in a voltaic cell in which selenium is an electrode (Sabine, 1878).

The efficiency of an apparatus for the detection of light is the ratio of the amount of measurable effect it indicates to the amount of light received by the apparatus. Both the above actions being static, the amount of light available is best stated in terms of the steady flux of light, the unit being the lumen, or the amount of light falling upon 1 sq. m. distant 1 m. from a source of 1 candle-power.

Hitherto it has been customary to specify the "sensitiveness" of a selenium preparation by stating the ratio in which its resistance is reduced by a given illumination, reckoned in metre-candles ("lux"). This practice, however, gives no indication regarding the useful effect to be obtained from a restricted amount of light, such as that spreading out conically from a star image, as this depends upon the extent of the sensitive surface to be covered. Since the effect obtainable with a given selenium preparation is directly proportional, as a rule, to its sensitive surface, the latter has to be taken into account in determining its efficiency, and this is done by specifying the light in lumen rather than lux.

The Voltaic Efficiency.

Selenium "cells," properly so called, are electrolytic cells in which the illuminated selenium forms one of the electrodes and generates an E.M.F. Their efficiency should be defined as the E.M.F. in volts generated per lumen when the illumination is 1 lux. The illumination must be specified, since the E.M.F. is proportional to the square root of the incident energy.

Thus, in the arrangement adopted by Minchin* for the selenium photometry of stars, 0·03 volt was obtained by illuminating a sensitive surface of 0·645 sq. cm. by means of a candle at a distance of 274 cm. The illumination was 0·133 lux. With unit illumination, the E.M.F. would have been 0·0822 volt. Then the flux of light intercepted by 0·645 sq. cm. would have been 64·5 microlumen, and the resulting voltaic efficiency is 1270 volts per lumen.

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* G. M. Minchin, 'Roy. Soc. Proc.,' 1895, vol. 58, p. 142; and 1896, vol. 59, p. 231.

The Galvanometric Efficiency.

Selenium "cells" in which the action due to light is a change in the resistance of selenium are more properly termed selenium "bridges" (Minchin). The problem here presented for solution is not so much to obtain the largest possible ratio of "dark" to "light" resistance, but the largest absolute increase of conductivity, *i.e.* the largest additional *current* on exposing to light. In this respect, the most "sensitive" bridges may be comparatively useless unless they also have a reasonably low resistance, and this it has always been found difficult to secure.

The "galvanometric efficiency" may be defined as the increase of conductivity produced in a selenium bridge under unit flux of light. Convenient numbers, applicable to most bridges made, are obtained if the conductivity is reckoned in reciprocals of megohms ("micromhos") and the flux of light in lumen. Thus, a selenium bridge 10 cm. square, placed at 1 m. from a 100 candle-power source, would receive 1 lumen of light. If, under those circumstances, its resistance changed just as it would if a megohm were connected in parallel with it, its "galvanometric efficiency" would be unity.

Observed Efficiencies.

The data hitherto published with regard to the results obtained by means of selenium preparations are often insufficient for determining their efficiencies. M. Reinganum,[*] using photo-voltaic selenium cells with a sensitive surface of 5·9 sq. cm., obtained about 0·12 volt with a Nernst lamp placed at 30 cm. This gives a voltaic efficiency of about 6 volts per lumen at normal illumination if the square root law holds good for intense illuminations. Low as this efficiency is, it is probably considerably above that obtained by v. Uljanin[†] in 1888, who observed 0·12 volt in sunlight (about 50,000 lux).

As regards galvanometric efficiencies, the greatest interest, from the point of view of the present investigation, attaches to the figures given by Stebbins,[‡] who recently studied the light-curve of Algol by means of a selenium bridge. The light from the star was received by the 12-inch objective of a refractor, and an extra-focal image 0·7 cm. in diameter was formed on a Giltay selenium bridge having a "dark" resistance of 3 megohms. The illumination due to the star was thus increased 1,900 times. Now, the illumination due to Arcturus is very nearly one microlux*. The stellar magnitudes of Arcturus and Algol at maximum are given by the Nautical Almanac as 0·3 and 2·2 respectively. Hence the "unaided" illumination by Algol will be 0·174 microlux, and the illumination of its extra-focal image 330 microlux. This illumination, falling on a surface of area 0·385 sq. cm., gives a light flux of 0·0127 microlumen.

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[*] M. Reinganum, 'Phys. Zeitschr.,' 1906, vol. 7, p. 786 ; and 1907, vol. 8, p. 293.

[†] v. Uljanin, 'Wied. Ann.,' 1888, vol. 36, p. 241.

[‡] J. Stebbins, 'Astrophys. Journ.,' 1910, vol. 32, p. 185.

The deflection shown by the galvanometer was 8 divisions. The deflection represented a current of $1{\cdot}92 \times 10^{-9}$ ampère. The voltage used was 6. Hence the additional conductivity was 0·00032 micromhos, and the "galvanometric efficiency" was 25,200 micromhos per lumen.

That a galvanometric efficiency of 25,200 is unusually great will appear from a calculation of the efficiency of a cylindrical bridge described by Ruhmer† as the best out of a number of bridges tested. The area exposed to an illumination of 4·6 lux was 14·2 sq. cm., giving a flux of 0·00653 lumen. The resistance fell from 35,000 ohms to half that value, which means an additional conductivity of 28·6 micromhos. Hence the efficiency is 4380 micromhos per lumen.

Another Ruhmer bridge, used by Korn‡ for picture-telegraphy, had an efficiency of about 234 micromhos per lumen in "diffused daylight" (about 1,000 lux).

Conditions Affecting the Efficiency.

In order to compare two selenium bridges under standard conditions, it is necessary to take into account a number of circumstances affecting their indications. These are the following:—

(a) *Colour.*—For the ordinary sources of light, the maximum effect shown by selenium is that due to the visible red, and as the maximum shifts with the distribution of energy in the spectrum, this distribution must be specified.

In practice, it will be most convenient to adopt a standard distribution of energy in the spectrum, such as is offered by one of the accepted standards of brightness. I suggest, as the standard illumination, that provided by the whole spectrum of Harcourt's pentane standard, the distance from the source being such as to give one lux. As an alternative, the Hefner lamp might be adopted.

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* G. M. Minchin (C. V. Boys), 'Nature,' 1895, vol. 52, p. 246. See also G. Müller, 'Die Photometrie der Gestirne' (Engelmann, Leipzig).

† E. Ruhmer, 'Phys. Zeitschr.,' 1902, vol. 3, p. 468.

‡ A. Korn, 'Phys. Zeitschr.,' 1904, vol. 5, p. 113.

(b) *Temperature.*—Stebbins* found that the sensitiveness of a selenium bridge was considerably increased by lowering its temperature permanently to 0° C. Pocchettino† found a reduction of 25 per cent. in the sensitiveness on plunging a bridge into liquid air. I found a reduction of 10 per cent. under the same circumstances.‡ I propose to adopt 15° C. as the most convenient standard temperature, freezing point being unsuitable for photo-voltaic selenium cells.

(c) *Voltage.*—The resistance of a selenium bridge depends upon the voltage, the percentage decrease of resistance being proportional to the logarithm of the applied voltage.‡ I propose 1 volt as the standard voltage. This has the advantage that the efficiency can be expressed in micro-ampères (instead of micromhos) per lumen. The voltage does not sensibly affect the sensitiveness, unless it is so high that the Joulean heating produces a perceptible rise in the temperature of the bridge, whereupon the sensitiveness decreases.

The wide divergence of results hitherto obtained with regard to the "sensitiveness" of selenium is attributable to the differences in method of exposure and of interpretation. The measurements are affected by the "inertia" of selenium, shown in the slowness with which it acquires its final conductivity when illuminated, and the even greater slowness of recovery in the dark.

In selenium bridges with graphite electrodes, in which there is no chemical action between the electrodes and the selenium, the changes of conductivity during and after faint illumination closely approximate to what they would be if due to a progressive ionisation of the selenium under the action of light, the number of ions produced in unit of time being proportional to the flux, and the total number proportional to the total quantity of light, less whatever ions recombined. The equation to the light-action curve is then

$$dN/dt = C - BN^2,$$

where C is proportional to the flux of incident energy and B is the coefficient of recombination. N is the additional conductivity, and is proportional to the number of ions of both signs liberated. In a steady state $C = BN_0^2$, or the final steady conductivity N_0 is proportional to the square root of the light intensity (as actually found by Rosse, Adams, Berndt, and Minchin).

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* J. Stebbins, *loc. cit.*

† Pocchettino, 'Rend. R. Accad. dei Lincei,' 1902, vol. 11, p. 286.

‡ E. E. Fournier d'Albe, 'Roy. Soc. Proc.,' 1912, A, vol. 86, p. 452.

By integration we get

$$N = \sqrt{(C/B)}\tanh(t\sqrt{C}),$$

or

$$t = \frac{1}{2BN_0}\log\frac{N_0+N}{N_0-N}.$$

The tanh-curve has an initial straight line portion inclined to the N-axis, so that before recombination becomes considerable the change of conductivity on illumination is proportional to the incident energy, as is found to be the case for all feeble exposures.

For the recovery curve we have, by integrating $dN/dt = -BN^2$, the relation

$$\frac{1}{N}-\frac{1}{N_1} = Bt,$$

where N_1 is the additional conductivity at the moment of shutting off the light. N_1 may be most conveniently obtained from the recovery curve itself. If the galvanometer deflection at the moment of obscuration is called zero, and d_1, d_2 are two readings taken at equal time-intervals after that moment, then

$$N_1 = \frac{d_1 d_2}{2d_1-d_2}.$$

This N_1 is the final value attained by the recovery after a very long time. It is hereinafter called the "total recovery," and designated by R. It is, other conditions being equal, the net additional conductivity due to previous illumination, whatever may have been the method of exposure. But since the rapidity of reaction varies greatly with the intensity of the light, it is best to adopt a method of exposure in which the light action has a definite relation to the recovery. This is attained by alternately exposing and obscuring for equal times until the curve oscillates between steady values. Then the number of ions produced by illumination is twice the number recombined in the same time, and if the number produced varies as the incident energy, the amplitude of oscillation will also vary as the incident energy. This is shown below to be very approximately the case.

Thus the process proposed for determining the true increase of conductivity for a given illumination is the following :—

Illuminate and darken for alternate periods of one minute each, and when the "light" and "dark" deflections have each become consistent, shut off the light finally and take readings after the first and second minute.

The conditions proposed for determining the normal galvanometric efficiency of a selenium bridge may here be summarised :—

(*a*) Quality of light: complete radiation from a standard pentane lamp.
(*b*) Illumination: 1 lux.
(*c*) Voltage: 1 volt.
(*d*) Temperature: 15° C.
(*e*) History: alternate light and darkness for one minute each until steady state is attained.
(*f*) Measurement: readings for successive minutes during recovery. Evaluation of the "normal galvanometric efficiency" in micromhos per lumen, in this case equivalent to micro-ampères per lumen, or micro-ampères per square centimetre of sensitive surface, divided by 0·0001.

The Detection of Small Fluxes of Light.

A preliminary experiment to test the efficiency of selenium in detecting small fluxes of light was made as follows:—A thin rod of highly insulating porcelain was ground flat at one end, offering a circular surface 0·1 sq. cm. in area. Thick pencil lines were drawn along two opposite generators of the cylindrical surface, and a cap of selenium was thinly spread over one end. The selenium was then sensitised in the usual manner by annealing, and the rod was inserted in a hole bored through a stick of ebonite, and fixed by means of binding screws. When not exposed, the selenium was covered with a cap fitting over the aperture. This miniature selenium bridge is shown in fig. 1. Its resistance, when freshly prepared, was 50 megohms.

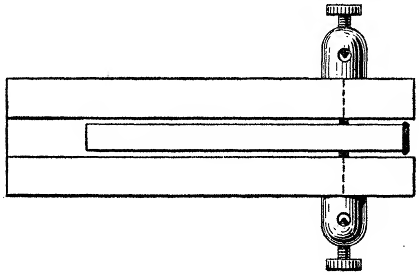

Fig. 1.

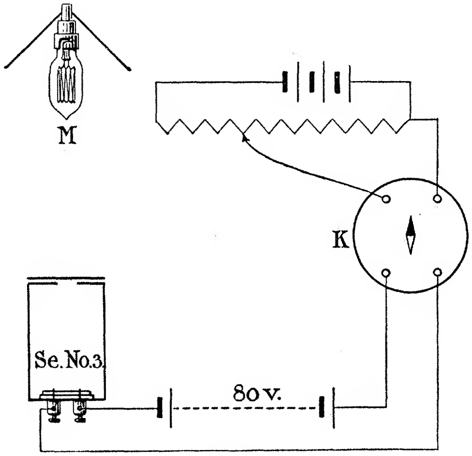

Fig. 2.

It was inserted into a circuit containing a battery of 20 volts and a Broca (consequent pole) galvanometer giving 0·6 division for 10^{-9} ampère. The "dark" deflection was compensated by suitably altering the magnetic field, and the selenium was then exposed to various moderate illuminations. The faintest illumination discoverable with certainty proved to be that due to a paraffin candle 5 m. from the selenium. This illumination was 0·04 lux, and the light flux received on the sensitive surface was 0·4 microlumen. The deflection was 5 divs. = 0·003 micro-ampère. This means an additional conductivity of 0·00015 micromhos, and a galvanometric efficiency of 375 micromhos per lumen.

Both these efficiencies are low, and as the sensitive surface is of about the same area as the pupil of the eye, this method evidently falls far short of the capability of the human eye in detecting a candle at 5 m.

Better results were obtained by charging a condenser through the selenium resistance and discharging it ballistically, but it was difficult to obtain consistent readings.

Electrometer Methods.

A Dolezalek quadrant electrometer giving 200 divisions per volt was used to measure the resistance of some high resistance selenium bridges, either by Cardew's method, or by inserting it in the galvanometer branch of a Wheatstone bridge. A change of 1/30th per cent. in the resistance was thus observed, due to an illumination of 0·001 lux. The galvanometric efficiency was of the order of 300 micromhos per lumen.

Results with Differential Galvanometer.

The best results, both as regards actual deflections and galvanometric efficiencies, were obtained with a Kelvin differential galvanometer having coils of a total resistance of 6280 ohms.

In order to be able to vary the illumination measurably within wide limits, the arrangement shown in the diagram (fig. 2) was adopted. The selenium bridge Se No. 3 was fixed on the bottom of the box B, which was optically blackened inside. At a distance of 25 cm. above the selenium was a circular opening 25 sq. cm. in area, closed by a plate of ground glass. A metallic filament lamp M was placed above the box at such a distance that the total candle-power of the ground-glass disc, as seen from the bottom of the box and determined photometrically, was 0·125. The illumination at the bottom of the box was thus 2 lux when the ground glass was lighted to give $\frac{1}{8}$ candle-power. By placing a small diaphragm on the ground-glass surface, the illumination could be reduced to any desired amount. The faintest illumination so obtained was 10 microlux, or ten times that due to Arcturus unaided Since this was discovered by means of a selenium bridge, it means that it is possible to discover bright stars by means of selenium without the aid of any optical system whatever.

As ground glass does not necessarily give an illumination uniform over a wide angle, the precaution was adopted of picking out central, intermediate, and marginal portions of the ground glass in turn. Under the conditions here described no difference due to this shifting was discoverable, so that for the purposes of these measurements, as well as others described below, the ground glass may be considered as equivalent to a uniformly self-luminous surface.

One of the coils of the differential galvanometer K was put in circuit with a battery of accumulators, giving 80 volts, and the selenium bridge. The other coil, which had the same resistance, was traversed by a compensating current of the order of 6 micro-ampères.

A set of diaphragms was made by drilling round holes of different diameters in a piece of sheet copper. Complete series of measurements were made with four of these, called A, B, D, and E respectively. Two smaller ones, called F and G, gave somewhat uncertain results because the instrumental errors began to be comparable with the quantities to be measured.

The following table gives the diameters and areas of the apertures used, and the candle-power of the small circle of ground glass they exposed to the light, together with the illumination produced by that candle-power at the distance of the selenium bridge (25 cm.).

	Diameter.	Area.	Candle-power.	Illumination.
	cm.	cm.^{2}.	micro-candles.	microlux.
A	0·370	0·108	540·0	8640·0
B	0·305	0·0730	365·0	5840·0
D	0·207	0·0337	169·0	2704·0
E	0·107	0·0090	45·0	720·0
F	0·04	0·00126	6·3	100·8
G	0·025	0·00049	2·45	39·2

The galvanometer having been made nearly aperiodic, readings were taken after half a minute's exposure, then after half a minute's recovery, and so on alternately until successive "dark" and "light" readings had become sensibly constant. The exposures were made either by moving a light cardboard shutter or by switching on the lamp, the room being otherwise in complete darkness. Finally, the shutter having been closed, readings were taken for five or six half minutes in order to determine points on the "recovery" curve. The timing was done by listening to the beats of a metronome marking seconds.

The accompanying diagram (fig. 3) gives the readings so obtained in the case of aperture A.

On joining up the "light" and "dark" readings respectively, two curves are obtained whose vertical distance apart we may call the "amplitude" of the alternating exposure curve. These readings, therefore, give us two main results: the "total recovery" R, calculated as explained above, from two ordinates in the recovery curve; and the "amplitude" P. Both these quantities should be plotted against the illumination I, in order to discover the laws of the light action. This is done in fig. 4, which gives the total recoveries after various illuminations, and fig. 5, which gives the amplitudes for the same illuminations.

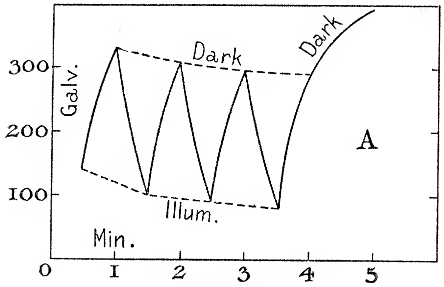

Fig. 3.

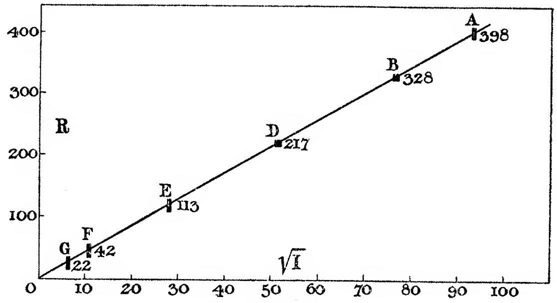

Fig. 4.

The values for the apertures F and G were too small to be obtained in the same way. They were somewhat roughly estimated by waiting until the deflection in the light seemed to approach a final value, then darkening and waiting until the recovery seemed to do the same, and taking the mean of the two deflections for the "total recovery."

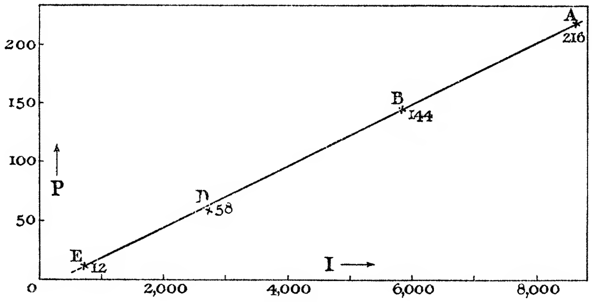

Fig. 5.

The following conclusions can be drawn from these curves:—

(*a*) The amplitude is proportional to the illumination. The curve is a straight line, which, however, does not pass through the origin, and probably has a curved portion between E and the origin (fig. 5).

(*b*) The total recovery is proportional to the square root of the illumination. This appears to hold rigidly down to the feeblest illuminations, as far as the limits of accuracy allow one to judge. These limits are indicated in the curve (fig. 4) by rectangles including all admissible values of the illumination and of the total recovery.

(*c*) The ratio of amplitude to total recovery is proportional to the square root of the illumination. This follows from (*a*) and (*b*), and is subject to the error specified under (*a*) for very faint illuminations.

One division (1 mm. at 1 m.) of the galvanometer scale represented a current of 0·00202 micro-ampère. This, with 80 volts, means that each millimetre of deflection indicates a gain or loss of conductivity amounting to 0·0000252 micromhos. Hence the "galvanometric efficiency" of the selenium bridge Se 3 is given by the following figures, which, of course show an efficiency inversely proportional to the square root of the illumination.

	Flux.	R.	Difference of conductivity.	Galvanometric efficiency.
	microlumen.	mm.	micromhos.	
A	0·864	398·0	0·010	11500
B	0·584	328·0	0·0083	14200
D	0·2704	217·5	0·00543	20100
E	0·0720	113·0	0·00285	39500
F	0·01008	41·0	0·001035	102000
G	0·00392	26·0	0·000655	167000

To discover still fainter illuminations, a minute hole, 0·013 cm. in diameter, was pricked in tinfoil, thus giving an illumination of 10 microlux (about that due to Venus unaided). It was not discoverable with certainty by means of bridge Se No. 3, but was easily discovered by means of a bridge of resistance 20,000 ohms, which could be worked with 15 volts. The "amplitude" was 11·1 divisions, derived from 20 alternate readings, during which, however, there was a strong drift owing to change of temperature. The efficiency is the same as in case of hole G.

Comparison with Potassium Photo-electric Cell.

It is of interest to compare the above results with the best performance of a potassium photo-electric photometer described by Elster and Geitel.[*] They placed a minute hole 0·038 sq. mm. in area in front of an amyl acetate lamp at 9·3 m. The illumination thus received was 3 microlux. The photo-electric current was then $6{\cdot}7 \times 10^{-14}$ ampère. With 10 microlux, in the last experiment, the current was 0·0222 micro-ampère. Selenium, therefore, with the same illumination and extent of sensitive surface, is capable of giving a measurable effect at least 100,000 times greater than that furnished by a potassium photo-electric cell.

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[*] J. Elster and H. Geitel, 'Phys. Zeitschr.,' 1912, vol. 13, pp. 468 and 739.

Comparison with the Human Eye.

The sixth magnitude is usually assumed as that of the faintest star clearly visible to the naked eye. Zöllner estimated the ratio of the brightness of the sun and Capella as 55,700,000,000. The sun's vertical illumination has been put at 50,000 lux (Exner). This would make the illumination due to Capella (magnitude 0·2) 0·9 microlux. A star of magnitude 5·2 would then give an illumination of 0·009 microlux, and an illumination one-third of that would have to be considered the limit of human vision. Let us call it 3 milli-microlux.

An attempt to test this limit experimentally was made as follows:—A 10-volt 1 candle-power electric lamp was encased in a cylinder closed with a disc of ground glass. To secure an even illumination of the latter, the cylinder was lined with white cardboard. An image of this disc was thrown by a lens on to another ground-glass screen G. The lens was stopped down by an iris diaphragm until the whole luminosity emitted by the screen G approached the limit of accurate comparison with a pentane lamp. At that point, the candle power of G, in the direction of the original beam produced, was found to be 0·00142, as compared with the pentane standard. The experiments were conducted in a dark room, and the eye was carefully protected from all stray light.

Further reductions were then made by inserting small measured stops into the iris diaphragm. When the area of the stop was 0·0007 sq. cm., the computed candle power of the illuminated surface of G, 5·7 sq. cm. in area, was 0·125 micro-candle. A faint "star" was then produced by placing a small stop on the ground glass G. A stop of area 0·0064 sq. cm. was not visible at all. A stop of area 0·0079 sq. cm. was visible after 10 minutes' accommodation to complete darkness, and a stop of area 0·0178 sq. cm. was clearly visible. Averted or "rod" vision was employed in every case as a final test. The object was 20 cm. from the eye. The candle powers were respectively 0·142, 0·175, and 0·395 milli-micro-candles. The illuminations at 20 cm. were 3·55, 4·36, and 9·9 milli-microlux respectively. Another observer obtained the same results, except that it was very difficult to perceive the second stop. On the whole, the results show a satisfactory agreement with the star estimates.

It was next attempted to find the limit of visibility of a faintly illuminated *surface*. The surface examined was the ground glass G, with the iris diaphragm stopped down by means of very minute holes pricked in tinfoil.

The results showed that a surface becomes invisible when its intrinsic brightness is less than 4×10^{-10} candles per square centimetre; 1 sq. cm. of the barely visible surface gives an illumination of 10 milli-microlux at 20 cm. If its brightness were concentrated at a point, that point would be clearly visible. The eye, therefore, suffers in sensitiveness when the light is diffused. The selenium detector does not. If the two were equally sensitive to a point source, the selenium detector would be more sensitive than the eye for faintly illuminated surfaces.

The fluxes of light discoverable by the eye are very minute. In the dark, the diameter of the pupil is about 6 mm., and its area 0·28 sq. cm. With an illumination of 3 milli-microlux, the flux received is $8{\cdot}5 \times 10^{-14}$ lumen. This is, therefore, the minimum flux of light perceptible to the eye.

The Theoretical Instrument Limit.

The limit reached with the experimental arrangements described above is still very far removed from the limit theoretically attainable with the most sensitive instruments now available. This is evident from the fact that a potassium photo-electric cell closely approaches the efficiency of the eye, although the current obtainable from it is 100,000 times feebler than the current furnished by the selenium bridge. Elster and Geitel worked with currents of the order of 10^{-14} ampère, which represents approximately the present-day limit of current measurement. Now if a current of the order of 10^{-9} ampère is obtained with an illumination of 10 microlux, a current of 10^{-14} ampère should, if the square-root law holds throughout, be obtainable with an illumination of 10^{-9} microlux, or the unaided illumination of a star of the 23rd magnitude, which is invisible in the most powerful telescope hitherto constructed. If, on the other hand, the current amplitude varies simply as the illumination, an illumination of 0·01 milli-microlux should be discoverable, which is at least 100 times less than that discoverable by the eye, so that stars of the 11th magnitude should show an electric effect unaided. This advantage over the eye would be kept whatever the optical system, so that a larger telescope would give no advantage to the eye without giving it to the selenium detector to the same extent. Selenium, therefore, offers an extension of our field of perception far beyond present optical or even photographic limits.

Bearing on the Theory of Quanta.

The efficiency of a lamp which converts the entire energy supplied to it into luminous radiation of the most visually advantageous type is 55 candles per watt. This value, given by Buisson and Fabry,* is intermediate between the values found by Drysdale and by Hyde, who obtained 17 and 72 respectively. That portion of the total flux of energy from a Hefner lamp which lies within the visible spectrum is about 200,000 ergs per second. The portion intercepted by 1 sq. cm. at 1 m. is 1·6 erg per second. This is the equivalent of 100 micro-lumen, and the illumination is 1 lux.

The eye, as we have seen, can perceive an incident luminous energy of $8{\cdot}5 \times 10^{-14}$ lumen, which is equivalent to 1360×10^{-12} ergs per second.

Planck's† energy quantum for a frequency n is $6{\cdot}55 \times 10^{-27} \times n$ erg. For a frequency $0{\cdot}58 \times 10^{-15}$, which is that of maximum visibility, the quantum is $3{\cdot}8 \times 10^{-12}$ erg.

The number of quanta received by the eye when receiving the minimum visible light is, therefore, about 360 per second. Any instrument, therefore, which has a sensitiveness 1000 or more times greater than that of the eye may be effective in discovering discontinuities in the light emission at feeble illuminations. As selenium is by far the most efficient detector known, the efforts in this direction made by N. Campbell‡ with Na-K alloy cells should be repeated with selenium bridges.

Effect of Invisible Radiations.

In comparing the efficiency of selenium with that of the eye or of other detectors, it is necessary to deduct the effect of the invisible spectrum. The maximum energy of most terrestrial sources of light is in the infra-red, and if selenium were, like the bolometer or the thermopile, simply a detector of radiant energy, its performances in detecting sources of terrestrial radiation could not be regarded as evidence of superiority in detecting visible radiations.

In order to study this question experimentally a new form of selenium bridge was constructed, consisting of a porcelain rod 0·25 cm. in diameter and 5 cm. long. Two thick parallel pencil lines were drawn lengthwise along the rod, leaving a clear white line 0·05 cm. wide and 4 cm. long between them. The white line was then bridged over with selenium, which was then sensitised. The result was a "line bridge" suitable for spectroscopic work. After constructing 12 such elements the most sensitive was chosen. It had a normal galvanometric efficiency of 250 micromhos per lumen.

This line bridge was exposed to the spectrum of a Nernst lamp produced by a 60° flint glass prism. The visible spectrum was 5·5 cm. long. That portion which affected the selenium was not longer than 8 cm. It was divided into half centimetres, and the line bridge was successively placed at each division. Half minute "amplitudes" were taken for each position, moving the bridge first from ultra-violet to infra-red and then in the opposite direction. The mean amplitudes so obtained for each position were divided into two groups, those for the invisible spectrum and those for the visible spectrum respectively. Expressed in percentages of the total radiation the effective energies were—

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* Buisson and Fabry, 'Comptes Rendus,' 1911, vol. 153, p. 254.

† M. Planck, 'Ann. der Phys.,' 1901, vol. 4, p. 553.

‡ N. Campbell, 'Camb. Phil. Soc. Proc.,' 1910, vol. 15, p. 513.

Ultra-violet	1·4
Visible	72·8
Infra-red	25·8
	100·0

Although it is evident that the invisible radiations are not in the aggregate as effective as the visible rays, the above figures do not necessarily represent the quantitative distribution of the effective energies. The latter cannot be accurately obtained without ascertaining the law of light action for each radiation separately.

This was done by Pfund* for short exposures and for two different intensities. He found a somewhat abrupt transition at a wave-length of 6500 Å.U. Below that wave-length the deflection was proportional to the square root of the energy, while from 7000 Å.U. to the end of the spectrum it was simply proportional to the energy. I have already mentioned that the deflections so obtained are not necessarily proportional to the total effect, and a more detailed investigation of the law of light action will be necessary for each part of the spectrum. Meanwhile, the following qualitative experiment shows that the dissymmetry found by Pfund does not apply to the final deflection.

The Nernst lamp spectrum was allowed to fall on a ground-glass screen closing the front end of a tube 43 cm. long, lined with white cardboard. Any portions of the spectrum could thus be recombined separately, and the selenium bridge at the other end received a definite portion of the aggregate energy of whatever parts of the spectrum were transmitted through the ground glass. The spectrum was divided into two portions which exerted equal actions. The division proved to be slightly on one side of the line C towards the blue. The separate effects were always in the aggregate greater than the total effect, showing that the effect varies as a power of the energy below the first power. The slit of the spectroscopic arrangement was then narrowed or widened, and the selenium exposed alternately to the two portions, as before. The intensity was thus varied in the ratio of at least 5 : 1, but the total deflections were sensibly equal for both portions. This shows that there is no great difference in the exponent of the energy for the two branches of the resonance curve.

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* A. H. Pfund, 'Phys. Rev.,' 1912, vol. 34, p. 370.

The general result for the spectral distribution of the effective energy is that about three-quarters of the total effect are due to visible radiations, even when the energy maximum is in the infra-red, as it is in most terrestrial sources. This proportion is maintained, or exceeded, with faint illuminations. If Pfund's relation held good, selenium would be sensible to none but those radiations which belong to the visible spectrum, if the light were faint enough. In any case, only some 30 per cent. at most need be deducted from the observed effect in selenium in order to reduce it to visible light.

The Detection of Small Changes of Brightness.

The limit of accuracy in photometric estimates is generally recognised to be ½ per cent., and as there is no optical means of increasing the contrast of two extended surfaces, a limitation is thus imposed upon the estimation of brightness such as physicists are not content to accept in other measurements. Contrast can be increased by photography almost indefinitely,* but it is a lengthy process, and gives no measure of the original contrast. It is therefore of interest to inquire whether selenium, besides being efficient as a detector of feeble light, is superior to the eye as regards the appreciation of minute differences of illumination.

To take a concrete case. A selenium bridge of efficiency 1000 will give 1000 micro-ampères with one volt if its surface is 1 sq. m. and the illumination 1 lux. With an illumination of 10,000 lux (feeble sunlight) the current will be 100,000 micro-ampères (assuming the square-root law), or 10 micro-ampères if the sensitive surface is only 1 sq. cm. A difference in the illumination amounting to 1 per cent. will make a difference of ½ per cent. in the current, or a difference of 0·05 micro-ampère (say, 100 divisions on the scale of a sensitive galvanometer). There is, then, no reason why a difference of 0·01 per cent. should not be electrically discovered, which, of course, is quite beyond the power of the eye.

This conclusion was confirmed by a number of experiments, one of which was the following :—

A ground-glass disc, 25 sq. cm. in area, was illuminated by a lamp from above. The disc then transmitted a light equivalent to 1/8 candle. A selenium bridge placed 25 cm. below the disc was exposed to this light, and was connected up to a P.O. resistance box. A battery of 8 volts and a Broca galvanometer adjusted to give 100 divisions per micro-ampère were also connected up. Adjustment being made for equilibrium, a black thread $\frac{1}{4}$ mm. thick was drawn across in contact with the ground glass surface. When passing across the centre of the disc it shaded off 0·6 per cent. of its area. A deflection of 8 divisions was obtained on the galvanometer. With 20 volts a deflection of 20 divisions was obtained. It was possible, then, to discover a variation of 0·03 per cent. with this comparatively insensitive arrangement. It is evident, therefore, that for such purposes as photometry and half-shadow polarimetry the selenium bridge must become a valuable accessory, capable of bringing these measurements up to the level of accuracy of other standard physical determinations.

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* E. E. Fournier d'Albe, 'Roy. Dub. Soc. Proc.,' 1909, 12, vol. 11, p. 97.

Summary.

1. The efficiency of selenium preparations used for detecting light is strictly defined, and standard conditions are chosen for determining it.
2. The efficiencies of some selenium preparations are evaluated from data given in previous publications.
3. Experiments are described which were made in order to detect minute quantities of light by means of selenium.
4. The minimum illumination reached is 10 microlux.
5. The law of light action is investigated, and shown to be, in the main, a square-root law, down to the feeblest illuminations.
6. The theoretical limit of light action discoverable by means of present-day methods and apparatus is calculated, and shown to be, with selenium, very far beyond the power of the eye.
7. It is shown that this offers a means of deciding the question of the discrete structure of radiant energy (theory of quanta).
8. It is shown, theoretically and experimentally, that selenium apparatus is capable of discriminating differences and variations of luminosity quite inappreciable to the eye.